Effectiveness of Whole Linted Cottonseed as a Replacement for Forage Fiber in Diets Varying in Starch Availability

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Abstract

Six primiparous Holstein cows (ruminally and duodenally cannulated) in a 6 x 6 Latin square design were used to determine the relationship between the physical effectiveness of whole linted cottonseed (WCS) and its level of forage substitution when diets varying in starch availability were fed. This relationship was evaluated based on stimulation of chewing activity, maintenance of milk fat percentage, intake, ruminal pH, and volatile fatty acid (VFA) concentrations. Diets were nutritionally equivalent; however, dietary composition differed in the amount of forage neutral detergent fiber (fNDF) supplied by alfalfa silage. Diets consisted of 1) high forage control with ground corn (FCG; 21% fNDF); 2) 5% WCS with ground corn (LCG; 18% fNDF); 3) 10% WCS with ground corn (MCG; 15% fNDF); 4) 15% WCS with ground corn (HCG; 12% fNDF); 5) 5% WCS with steam-flaked corn (LCSF; 18% fNDF); and 6) 10% WCS with steam-flaked corn (MCSF; 15% fNDF). Chewing activity (minutes/day) was unaffected by the level of WCS substitution for fNDF and corn source. However, ruminating and total chewing activity per kg of fNDF intake quadratically increased ($P < 0.05$) with level of WCS substitution. Even though milk fat percentage was similar between the FCG and LCG diets (3.67 and 3.69%), milk fat percentage tended to quadratically decrease with level of WCS substitution ($P < 0.05$). Substituting steam-flaked corn for ground corn decreased milk fat percentage substantially ($P < 0.05$). The addition of WCS to the diets quadratically increased ($P<0.05$) dry matter intake (DMI) and fNDF intake. However, replacing ground corn with steam-flaked corn decreased ($P<0.05$) DMI, neutral detergent fiber intake, and fNDF intake. Average ruminal pH decreased linearly ($P<0.05$) as level of WCS substitution increased. Even though molar concentration of acetate in the

rumen was unaffected by level of WCS substitution and corn source, molar concentration of propionate in the rumen linearly increased ($P<0.05$) with level of WCS. Additionally, substituting steam-flaked corn for ground corn increased molar concentration of propionate ($P<0.05$). Lack of WCS x corn source interactions suggests that the effectiveness of WCS is not affected by availability of rumen degradable starch. Whole linted cottonseed is as physically effective as alfalfa silage at stimulating chewing activity in diets with at least 12% fNDF, but it is not as effective at maintaining milk fat percentage in diets with less than 18% fNDF.

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Introduction

In today's dairy industry, many herds are approaching production levels that average 100 pounds of milk per cow per day. In order to achieve and maintain these high levels of production, it is necessary to feed energy-dense diets that contain large amounts of highly fermentable feeds, such as starch from grains. These energy-dense diets may result in increased production of fermentative acids by the rumen microorganisms during degradation. Such an increase in the production of fermentative acids has been associated with a decline in rumen pH that can lead to decreased rumen activity (Allen, 1997). To prevent the occurrence of disorders associated with decreased rumen activity and to maximize production, rations must be carefully formulated, with particular attention being given to the amount of dietary fiber included in the diet.

Fiber is necessary to obtain optimal dry matter and NE_L intake, to maintain normal rumen activity and milk fat percentage, and to possibly aid in the prevention of postpartum disorders (NRC, 1989). Fiber has been shown to stimulate chewing activity, which directly induces saliva secretion. This is crucial to maintaining the rumen environment because saliva acts as a buffer to compensate for the production of fermentative acids during microbial degradation of feedstuffs. Additionally, fiber has been shown to possess the ability to dilute the starch component of rations, which also aids in the maintenance of rumen pH. However, increasing dietary fiber from traditional fiber sources, such as forages, to compensate for increased production of fermentative acids is not always successful due to the limitations of gut fill. As a result, much attention has been focused on increasing the physical effectiveness of fiber sources in the diet via the substitution of non-forage fiber sources (NFFS), such as soybean hulls, brewers grains, distillers grains, and whole linted cottonseed (WCS).

Many factors must be taken into consideration by researchers and dairy producers before NFFS can optimally be used in a ration. These factors include the physical effectiveness of the fiber source, the starch dilution capabilities of the source, the availability of the starch in the ration, and the potential interactions that may occur between the NFFS and the forage components of the ration. These factors must be evaluated for each NFFS on an individual basis because they tend to vary widely.

Whole linted cottonseed is a unique feedstuff that exhibits considerable potential as a NFFS. Not only is WCS relatively high in fiber and energy, but it has also demonstrated the characteristics of physically effective fiber, including the stimulation of chewing activity (Clark and Armentano, 1993) and the maintenance of milk fat percentage (Kajikawa et al., 1991). However, the physical effectiveness of WCS appears to be dependent on the characteristics of the forage it replaces (Mooney and Allen, 1997). Moreover, the need for physically effective fiber increases as the concentration of ruminal degradable starch in the diet increases. Consequently, it can be expected that the forage source and level of ruminal degradable starch will dictate the amount of NFFS that can be used in the diet.

The purpose of this study was to evaluate the effectiveness of WCS as a NFFS when fed in diets with varying starch availability. This study was also conducted to determine the nature of the relationship between the physical effectiveness of WCS and its level of forage substitution.

Review of Literature

Fiber and the Physical Effectiveness of Fiber

The physical and chemical characteristics of fiber make it an essential component of the ruminant diet. Fiber, typically measured as neutral detergent fiber (NDF), is necessary to obtain optimum dry matter and NE_L intake, to maintain normal rumen activity and milk fat percentage, and to possibly aid in the prevention of postpartum disorders (NRC, 1989). Neutral detergent fiber is comprised of the cellulose, hemicellulose, and lignin components of plant tissue and has been shown to stimulate chewing, which results in the production of salivary buffers. These buffers are the most influential mechanism by which fermentative acids produced during the degradation of feedstuffs are neutralized (Erdman, 1988). The National Research Council (NRC, 1989) recommends that rations should provide a minimum of 25 to 28% NDF in the total dietary dry matter (DM); forages should supply 75% of the total dietary NDF. The NRC (1989) also suggests that at least one-third of the total dietary DM should be long hay or its DM equivalent as medium-to-coarse chopped silage or other forage. However, as diets become more energy-dense to satisfy increasing production demands, meeting the dietary fiber requirements of dairy cows is becoming more difficult.

Many energy-dense diets are high in readily fermentable carbohydrates that tend to increase rumen degradation, which is associated with increased production of fermentative acids. The increase in fermentative acid production must be compensated for to maintain rumen health and activity while feeding such an energy-dense ration. This could be accomplished by increasing dietary NDF, which would increase the flow of salivary buffers via stimulation of chewing activity. However, traditional sources of NDF, such as forages, tend to be bulky, and an increase in NDF could result in decreased dry matter intake (DMI) due to the constraints of gut fill (Dado and Allen, 1995). An alternate solution is to increase the physical effectiveness, rather than the quantity, of the NDF in the diet.

The physical effectiveness of a fiber source is defined as the ability of the fiber source to stimulate chewing, to maintain normal milk fat percentages and fat-corrected milk production, or both (Grant, 1997; Varga, 1997). Physical effectiveness varies among feed sources, primarily because of differences in feed particle size and rumen retention time (Allen, 1997). Additionally, interactions with other dietary components, such as nonfiber carbohydrates (NFC) or other fiber sources, may affect the apparent physical effectiveness of a fiber source. These variations and interactions have made it difficult to accurately quantify physical effectiveness. However, several methods of quantification have been proposed.

Welch and Smith (1969) established that NDF is the dietary component that stimulates chewing and were the first to quantify physical effectiveness by reporting the results in terms of minutes of chewing per kilogram of NDF intake. Soon after, Balch (1971) proposed an index of roughage value that was defined as total chewing time per unit of DM for various fiber sources. Later, Santini et al. (1983) determined a relationship between chewing activity and feed particle size and developed a roughage index that related feed particle length to total chewing time. Clark and Armentano (1993) assigned an effectiveness factor to various feedstuffs based on a linear regression coefficient that was calculated from the change in milk fat percentage divided by the change in NDF concentration when compared to a standard. More recently, Mooney and Allen (1997) developed a method to calculate a physical effectiveness coefficient for various fiber sources based on observed chewing times, percentage of fiber sources fed in the diet, and percentage of NDF in the feed components.

Physical Effectiveness of Fiber Relative to Ruminal pH and Chewing

The key feature that distinguishes ruminants from other species is their ability to successfully utilize fiber as a major source of energy. This is possible because of the populations of microorganisms that reside within the rumen. In order for these organisms to grow and function normally, certain environmental conditions must be maintained. The most important of these conditions is ruminal pH. The microbial population in the rumen grows optimally at pH 6.7 ± 0.5 (Van Soest, 1994). Deviations from this range may have implications upon rumen activity. For example, slight decreases in ruminal pH below 6.2 may decrease appetite, rumen motility, microbial yield, and fiber digestion (Allen, 1997). Substantial decreases in pH can lead to subclinical or acute symptoms of serious metabolic diseases such as laminitis, acidosis, and liver abscesses.

Ruminal pH is a function of the volatile fatty acid (VFA) production by bacteria, fungi, and protozoa in the rumen, absorption of VFA and water flux across the ruminal wall, saliva flow into the rumen, water flow into the omasum, and the cation exchange capacity of various feedstuffs (Erdman, 1988; Van Soest et al., 1991). While each of these factors play roles of varying degrees of importance in optimally maintaining the rumen environment, one of the most important is saliva flow into the rumen.

Saliva maintains ruminal pH by acting as a buffer. Salivary buffers neutralize hydrogen ions with bicarbonate and phosphate systems. The bicarbonate system involves the formation of carbonic acid as an intermediate. This intermediate is dissociated into water and carbon dioxide gas that is expelled by belching. The phosphate system involves the incorporation of hydrogen ions into dihydrogen phosphate. Both end products of these buffering systems, water and dihydrogen phosphate, flow through the omasum, thereby removing hydrogen ions from the rumen. Bailey and Balch (1961) estimated that the total buffering capacity of salivary buffers was 152 meq/L, which is approximately 41,500 meq/d. However, total buffering capacity is largely dependent upon the amount of buffer that enters the rumen via salivary flow. Studies strongly suggest that salivary flow rate is directly related to chewing activity, especially rumination (Allen, 1997; Cassida and Stokes, 1986).

The ability of a fiber source to stimulate chewing activity is one measure of fiber physical effectiveness (Allen, 1997; Armentano and Pereira, 1997; Beauchemin, 1991; Varga 1997). Total chewing time, which consists of total time spent eating and ruminating, is a function of fiber intake and feed particle size. A review by Allen (1997) showed that the concentration and intake of fiber were positively related to total chewing time across various experiments. Similarly, Beauchemin (1991) reported a linear increase in time spent chewing as dietary NDF increased (Table 1), and Armentano and Pereira (1997) suggested that forage NDF (fNDF) concentration had a strong positive correlation ($P < 0.01$) to total chewing time. Evidence presented by Armentano and Pereira (1997) also implied that NDF concentration was positively related to ruminal pH and the acetate:propionate ratio in the rumen.

The relationship between NDF concentration and ruminal VFA concentrations was examined by Beauchemin (1991). Results of the experiment suggested that total VFA concentration increased linearly as NDF concentration increased. An increase in NDF was also associated with increased acetate and butyrate and decreased proportions of propionate present in the rumen (Beauchemin, 1991). The association between NDF and ruminal VFA

Table 1. Effects of dietary neutral detergent fiber (NDF) concentration on daily chewing activity (Beauchemin, 1991).

	NDF[1]			P^2	
Chewing activity	31%	34%	37%	L	Q
min/kg NDF					
Eating	51.5	52.3	58.4	0.11	0.41
Ruminating	56.6	57.7	57.7	0.04	0.76
Total Chewing	108.1	109.9	116.2	0.55	0.44

[1]All values are based on alfalfa hay harvested in early bloom stage.
[2] L, Q = Linear and quadratic responses to concentration of dietary NDF.

concentrations may be attributed to the stimulation of chewing by NDF. As chewing increases, salivary buffer flow increases. Additionally, an increase in NDF concentration in the diet results in more fermentation of substrate by bacteria that do not make lactate or propionate, two byproducts of fermentation that can drastically lower ruminal pH. Consequently, rumen fermentation patterns may be altered, resulting in varying concentrations of VFA.

Chewing is also a function of feed particle size. Woodford and Murphy (1988) indicated that a reduction in feed particle size provided consistent reductions in time spent chewing (Table 2). Other trials have yielded similar results. Data compiled from 82 experiments showed that there were 160 more minutes of total chewing time for chopped forage (mean size $\geq$ 0.3 cm) and 317 more minutes of total chewing time for long hay than for finely chopped forage (Allen, 1997). Associated with reduced chewing time was a reduction in salivary buffer flow. Allen (1997) reported that substitution of finely chopped forage for coarse chopped forage decreased salivary buffer flow by nearly 5%. Consequently, feed particle size also plays a role in maintaining ruminal pH and VFA concentrations.

Although decreasing feed particle size did not affect the total VFA concentration in the rumen, it did increase the concentration of propionate and decrease the acetate:propionate ratio (Woodford and Murphy, 1988). This indicates that the rumen fermentation patterns were altered by the varying salivary flow rates. Woodford and Murphy (1988) also suggested that a substitution of alfalfa haylage (long particle size) for alfalfa pellets (small particle size) reduced the postprandial drop in ruminal pH due to an increase in saliva production during rumination.

Table 2. Effects of forage physical form on chewing activity (Woodford and Murphy, 1988).

	Diet		
	A[1]	B[2]	C[3]
Chewing Activity			
Eating, min/d	186	200	165
Ruminating, min/d	463[a]	367[b]	204[c]
Total chewing, min/d	650[a]	560[b]	380[c]

[1]Concentrate: alfalfa haylage: alfalfa pellets on DM basis was 60:40:0.
[2]Concentrate: alfalfa haylage: alfalfa pellets on DM basis was 60:28:12.
[3]Concentrate: alfalfa haylage: alfalfa pellets on DM basis was 60:12:28.
[a, b, c]Means within rows with unlike superscripts differ ($P<0.05$).

When considering the effect of physically effective NDF upon chewing activity, it is important to note that data suggest that cows possess an adaptive mechanism that maximizes the efficiency of rumination when NDF is limited. Grant (1997) reported that an increase in rumination per unit of fNDF intake occurred when NDF concentration was reduced. Similar results were noted by others (Beauchemin, 1991; Woodford and Murphy, 1988). Such an increase in chewing efficiency per unit of fiber intake may be indicative of the cell wall's resistance to mechanical breakdown, an increase in microbial digestion of forage, or an increase in the efficiency of primary mastication during eating. However, as Grant (1997) pointed out, this hypothesis cannot be clearly defined or substantiated because of a lack of data.

Physical Effectiveness of Fiber Relative to Milk Composition

Several researchers have suggested that milk fat percentage can be used as an indicator of the physical effectiveness of fiber (Armentano and Pereira, 1997; Varga, 1997). In contrast, others argue that milk fat is not a good indicator of physical effectiveness because milk fat is strongly affected by a variety of factors, including stage of lactation, genetics, the chemical properties of feedstuffs, and dietary composition (Mooney and Allen, 1997). While this opposing argument has its merits, using milk fat as a measure of fiber effectiveness seems logical given its relationships to fNDF ($P<0.01$), total chewing time, and VFA concentrations (Armentano and Pereira, 1997).

Although no direct relationship has been established, one of the factors that influences milk fat percentage is ruminal VFA concentration. Milk fat percentage tends to respond to the acetate:propionate ratio in the rumen; as the acetate:propionate ratio increases, milk fat percentage increases curvilinearly (Erdman, 1988). Coinciding with these results, Armentano and Pereira (1997) suggested that a weak positive correlation (r^2=0.16) existed between acetate:propionate ratio and milk fat percentage. Furthermore, evidence suggests that an increase in concentration of propionate is associated with milk fat depression, and that acetate:propionate ratios less than 2.0 result in the greatest decline in milk fat percentage (Erdman, 1988). The exact mechanism by which this relationship exists is unknown, but several theories, such as the glucogenic theory and the trans fatty acid theory have been proposed (Gaynor et al., 1995; Grant et al., 1990)

Evidence strongly suggests that milk fat percentage is affected by dietary fiber concentration. Beauchemin (1991) reported that increased NDF in the diet corresponded to linear increases in milk fat percentage (Table 3). Data reviewed and presented by Armentano and Pereira (1997) also indicated that milk fat percentage was positively correlated to fNDF concentration ($P < 0.01$).

Milk fat percentage is also influenced by feed particle size. Grant et al. (1990) reported that milk fat percentage decreased from 3.8% for cows fed a coarse (3.1 mm mean particle size) ration to 3.0% for cows fed a fine ration (2.0 mm mean particle size; Table 4). It has been suggested that the effect of feed particle size on milk fat percentage is related to the proportions of VFA in the rumen. Reducing feed particle size has been shown to reduce molar percentages of acetate and to increase molar percentages of propionate in the rumen (Grant et al., 1990; Woodford and Murphy, 1988).

Table 3. Effects of dietary neutral detergent fiber (NDF) concentration on milk production and composition (Beauchemin, 1991).

	NDF[1]			P^2	
	31%	34%	37%	L	Q
Production (kg/d)					
Milk	27.00	26.80	25.00	0.09	0.70
FCM	22.70	23.20	22.80	0.32	0.44
Composition (%)					
Fat	2.86	3.08	3.30	0.10	<0.001

[1]All values are based on alfalfa hay harvested in early bloom stage.
[2]L, Q = Linear and quadratic response to concentration of dietary NDF.

Table 4. Average milk yield and milk composition as influenced by particle size of ration (Grant et al., 1990).

Item	Ration		
	Fine[1]	Medium[2]	Coarse[3]
Actual milk, kg/d	31.50	32.10	31.08
4% FCM, kg/d	27.52[b]	30.28[a]	29.49[a,b]
Milk fat %	3.00[b]	3.60[a]	3.80[a]

[1]Mean particle size average 2.0 mm.
[2]Mean particle size average 2.6 mm.
[3]Mean particle size average 3.1 mm.
[a,b] Means within rows with unlike superscripts differ ($P < 0.5$).

Non-forage Fiber Sources and Their Physical Effectiveness

Traditionally, by-products such as WCS, brewers grains, and distillers grains have only been utilized as protein or energy supplements in dairy cattle rations. Recently, though, many dairy producers have become interested in using these by-products as non-forage fiber sources (NFFS) to replace traditional forage in diets. The use of NFFS is especially important when quality or quantity of traditional forages is limited and when increasing dietary fiber via traditional forages threatens to limit DMI because of gut fill. Research has shown that NFFS can successfully be substituted for a portion of forages in diets. In fact, dietary fNDF can be reduced from >75% of total NDF (NRC, 1989) to ≤60% with NFFS substitution without endangering FCM production (Grant, 1997).

There are several important factors that must be considered before incorporating NFFS into a ration. These include availability, cost, methods of handling and storage, and, most importantly, fiber physical effectiveness. In general, fiber from NFFS is approximately one-half as effective as NDF from alfalfa silage at maintaining milk fat percentage (Swain and Armentano, 1994). In addition, physical effectiveness varies greatly among sources. These variations are due primarily to differences in feed particle size and rumen retention time (Allen, 1997). For example, soybean hulls and WCS are 20% and 85% as effective, respectively, as long grass hay, which hypothetically contains 100% physically effective NDF (Grant, 1997). On average, NFFS are less than one-half as effective as forage in stimulating chewing (Firkins, 1995). A trial conducted by Clark and Armentano (1993) indicated that the addition of WCS increased chewing time per day by 15.6%. Conversely, the addition of dried distillers grains to the same diet decreased chewing time per day by 4.0% (Clark and Armentano, 1993). The same trial also showed that some NFFS might effectively increase milk fat percentage but not stimulate chewing. As a result, metabolic diseases due to unfavorable ruminal pH may not be as effectively prevented.

Two other factors to consider before incorporating NFFS into dairy rations are the starch dilution capabilities of the NFFS and the interactions that may occur between forage and NFFS. Degradation of starch, a nonstructural carbohydrate, by rumen microbes often produces more fermentative acids than does the degradation of fiber. For this reason, forages play an integral role in high starch diets by stimulating salivary buffer production via chewing and by diluting starch, both of which help to maintain ruminal pH. The ability of forage to dilute the starch is dependent on the starch source and grain processing techniques that affect the rate and amount of starch degradation that takes place in the rumen. For example, steam-flaking corn makes starch more available to rumen microbes than dry-rolling corn (Crocker et al., 1997). The starch dilution capability of a NFFS is an especially important consideration since it may help to reduce the incidence of metabolic disorders due to low ruminal pH (Firkins, 1997). Based on the benefits of starch dilution, Firkins (1995) proposed that NDF from NFFS replaces fNDF with two-thirds efficiency. Consequently, it can be expected that ruminal starch digestibility will dictate the amount of NFFS and minimum forage fiber concentration that can be used in a ration.

Interactions that occur between forage and NFFS may also affect the apparent physical effectiveness of NFFS. The small particle size and high specific gravity of many NFFS make them susceptible to increased ruminal rates of passage, which result in lower NDF digestibility (Grant, 1997). For example, increasing the amount of soybean hulls from 50% to 95% of a pelleted mix increased ruminal passage rate by 8%. Addition of coarse forage to diets that are high in NFFS, such as the previously described, improved fiber digestibility by nearly 32%. This may be due in part to an increased ruminal retention time, which allowed more extensive digestion to take place (Grant, 1997). As a result, it can also be expected that passage rates of NFFS will dictate the minimum amount of traditional fNDF needed to maintain adequate digestibility of fiber.

Whole Linted Cottonseed and its Potential as a Non-Forage Fiber Source

Whole linted cottonseed is a unique feedstuff that exhibits much potential as a NFFS because of its energy and fiber-dense characteristics (Kajikawa et al., 1991). Whole linted cottonseed provides 23.0% crude protein, 44.0% NDF, and 20.0% ether extract (NRC, 1989). Whole linted cottonseed is also readily available, being raised in the southern United States, and is relatively economical, ranging from $150 to $200 per ton in the Midwest. Most importantly, however, WCS induces the animal response factors that are associated with physically effective fiber: chewing and maintenance of milk fat percentage.

Whole linted cottonseed has been proven to effectively stimulate chewing activity. Based on total chewing time, Clark and Armentano (1993) reported WCS had physically effective fiber of 0.85 when compared to a standard of long alfalfa hay with physically effective fiber of 1.0. When 6% DM from WCS was added to a basal diet of 13% DM from alfalfa hay, a 10.1% increase in total chewing time occurred (Clark and Armentano, 1993). Furthermore, when WCS was substituted for 27% alfalfa haylage at two lengths, WCS was 127% more effective than short-cut alfalfa (5.8 mm mean particle size), but only 50% as effective as long-cut alfalfa haylage (11.4 mm mean particle size) at stimulating chewing and rumination (Mooney and Allen, 1997). These data strongly suggest that the physical effectiveness of WCS is relative to and dependent upon the physical effectiveness of the forage it replaces.

Whole linted cottonseed also effectively maintains or increases milk fat percentage. Clark and Armentano (1993) reported that WCS has adequate physical effective fiber to maintain milk fat when compared to alfalfa haylage NDF and has the potential to increase milk fat due to its crude fat content. Other trials have also reported maintenance of milk fat percentage with the substitution of WCS for forages (Hawkins et al., 1985; Kajikawa et al., 1991). The maintenance of milk fat percentages may be related to the effects of WCS on ruminal VFA concentrations. However, data concerning this are inconclusive. Clark and Armentano (1993) reported that the acetate:propionate ratio increased from 2.81 for the basal diet to 2.95 with the inclusion of WCS. In contrast, other trials have indicated that the addition of WCS had no effect upon VFA concentrations or even decreased acetate: propionate ratios (Arieli, 1998).

The substitution of WCS for traditional forage sources exhibits much potential. Whole linted cottonseed has been shown to maintain chewing activity and milk fat percentages, the two criteria most often used to quantify the effectiveness of fiber. However, the interactions of WCS with the forages it may replace and the effects of those interactions upon the physical effectiveness of the WCS have received relatively little attention. For this reason, this study was conducted to evaluate the potential interactions that may occur when WCS is substituted for traditional forage sources to meet NDF requirements and is fed with corn differing in starch availability. This study was also conducted to determine the nature of the relationship between the physical effectiveness of WCS and its level of forage substitution.

Materials and Methods

Experimental Procedures

Six primiparous ruminally and duodenally cannulated Holstein cows in mid-lactation were used in a 6 x 6 Latin square design. Cows were 130, 137, 134, 28, 140, and 161 days in milk (DIM; average 121.7 DIM) and weighed an average of 516.7 kg at the beginning of the trial. One cow was replaced prior to the beginning of the first period. Experimental periods were 21 days in length, with days one through nine being an adjustment period. Cows were immediately switched to new diets at the beginning of each period. Sampling occurred during days 10 through 21. Cows were housed in a conventional tie-stall barn on stall mattresses and were allowed access to concrete and sand lots during milking hours, except when chewing data were being gathered. Injections of bST were administered to all cows once every two weeks throughout the trial.

The experimental diets are shown in Table 5. All diets were alfalfa-silage based TMR. Diets were formulated to be equivalent in NDF, NFC, crude protein, degradable protein, crude fat, vitamin, and mineral composition. The high forage control diet, FCG, contained 21.0% NDF. The low WCS diets (diets LCG and LCSF) contained 18.0% forage NDF, the medium WCS diets (diets MCG and MCSF) contained 15.0% forage NDF, and the high WCS diet (diet HCG) contained 12.0% forage NDF. Diets FCG, LCG, MCG, and HCG used ground shelled corn as the energy source. Diets LCSF and MCSF substituted steam-flaked corn on a DM basis for the ground shelled corn.

All diets were mixed daily, and cows were fed equal proportions twice daily at 0600 and 1800 h. Feed offered and feed refused was recorded daily, and feed offered was adjusted

Table 5. Composition of diets.

Feed	Diet[1]					
	FCG	LCG	MCG	HCG	LCSF	MCSF
	(g/100g DM)					
Alfalfa Silage	53.00	44.70	38.00	30.27	44.70	38.00
Cottonseed	0	5.00	10.00	15.00	5.00	10.00
Cottonseed Hulls	0[3]	0.65[3]	0.93[3]	1.43[3]	0.65[3]	0.93[3]
Soyhulls (marked)[2]	1.10	1.10	1.10	1.10	1.10	1.10
Grain Mix Composition						
Corn Grain	27.716[3,4]	30.412[3,4]	31.633[3,4]	32.696[3,4]	30.412[3,5]	31.633[3,5]
Cracked Roasted Soybeans	14.407	9.877	4.798	0.000	9.877	4.798
Soybean Meal (48%)	0.000	3.622	7.143	10.370	3.622	7.143
Soy Hulls	2.134	2.634	2.772	3.111	2.634	2.772
Monosodium Phosphate	0.641	0.659	0.640	0.623	0.659	0.640
Magnesium Oxide	0.085	0.088	0.085	0.083	0.088	0.085
Limestone	0.320	0.593	0.832	1.037	0.593	0.832
TM Salt	0.480	0.494	0.480	0.467	0.494	0.480
Vit A-30	0.021	0.022	0.021	0.020	0.022	0.021
Vit D-3	0.042	0.044	0.042	0.041	0.044	0.042
Vit E	0.054	0.056	0.054	0.052	0.056	0.054

[1]Diets are as follows: FCG = Forage control with ground corn (21% fNDF); LCG =Low cottonseed with ground corn (18% fNDF); MCG = Medium cottonseed with ground corn (15% fNDF); HCG = High cottonseed with ground corn (12% fNDF); LCSF = Low cottonseed with steam-flaked corn (18% fNDF); and MCSF = Medium cottonseed with steam-flaked corn (15% fNDF).

[2]Soyhulls were labeled with chromium oxide for digestibility data for another study.

[3]Calculated using weighted averages to account for changes in dietary composition due to variations in dietary NDF during periods 4, 5, 6, and 7 versus periods 2 and 3.

[4]Corn grain ground.

[5]Corn grain steam-flaked.

for 10% refusal. Feed offered and refused and individual dietary ingredients were sampled during days 13 to 17. Samples were composited by period for cow and by period for ingredient and were lyophilized for analysis at a later time.

Chewing activity was monitored for one continuous 24-h period on day 10 of each period by observation of each cow every five minutes. No chewing activity observations were made while the cows were in milking (average time of 57 minutes each period). Chewing data were adjusted to total chewing activity during a 24-h period.

Cows were milked twice daily at 0530 and 1600 h. Milk samples were collected and milk weights were recorded twice daily during the a.m. and p.m. milkings on days 14 to 16. Milk samples were analyzed for milk fat by infrared spectroscopy (DHI Cooperative, Inc., Powell, OH).

Laboratory Analyses

Samples were ground through a 2-mm screen in a Wiley Mill (Arthur H. Thomas Co., Philadelphia, PA). Lyophilized samples were analyzed for DM, ash, and OM by the methods of the AOAC (1990). Feed fiber analysis (NDF, acid detergent fiber, and lignin) was performed according the method described by Van Soest et al. (1991). Prior to the addition of NDF solution, samples for fiber analysis were rinsed with 50 mL of hot ethanol and then soaked in 30 mL of 8 *M* urea and 0.2 mL of α-amylase overnight.

Rumen fluid samples were collected from the ruminal cannula at 3, 6, 9, and 12 h following the 0600-h feeding. Samples were strained through two layers of cheesecloth, and pH was determined immediately. An aliquot of sample was treated with 6 *N* HCl and frozen for analysis of VFA by gas-liquid chromatography (Firkins et al., 1990).

Calculation of Physical Effectiveness Coefficients

Physical effectiveness (pe) coefficients for WCS were calculated according to the procedure described by Mooney and Allen (1997). Coefficients were determined based on the premise that pe for alfalfa silage was 1.0. For the FCG diet,

$$TCT_{FCG} = B_0 + B_1G_{FCG} + B_2F_{FCG}.$$

For each diet with WCS, substituting B_2 from the previous equation,

$$TCT_C = B_0 + B_1G_C + B_2F_C + B_3W_c.$$

Then, pe = B_3/B_2 where

$TCT_{FCG, C}$ = total chewing time (minutes per day) for forage control diet (FCG) and WCS diets (C);

B_0 = basal chewing time (minutes per day) at 0% fNDF (percentage of DM); according to Mooney and Allen (1997), B_0 equals 355;

B_1 = chewing time (minutes per day) per unit of grain NDF (percentage of DM);

B_2 = chewing time (minutes per day) per unit of alfalfa silage NDF (percentage of DM);

B_3 = chewing time (minutes per day) per unit of WCS and cottonseed hulls NDF (percentage of DM);

$G_{FCG, C}$ = grain NDF (percentage of DM) for control diet (FCG) and WCS diets (C);

$F_{FCG, C}$ = fNDF (percentage of DM) for control diet (FCG) and WCS diets (C); and

W_C = WCS and cottonseed hulls NDF (percentage of DM) for WCS diets (C).

Treatment means for total chewing times were used for these calculations.

Statistical Analyses

Volatile fatty acid and pH data were analyzed using the PROC MIXED procedure of SAS (1997). Significance was declared at $P < 0.05$. All other data were analyzed according to the GLM procedure of SAS (1997). Preplanned contrasts were used for all data to determine the significance of differences among treatments (See Table 7). A contrast was also used to determine if an interaction occurred between the WCS and the corn source. Model effects were declared significant at $P < 0.05$ and trends were declared at $P < 0.10$, unless otherwise noted.

Results and Discussion

Nutrient Composition

The nutrient composition of the diets is shown in Table 6. Neutral detergent fiber values were higher than the formulated values of 28.0% for each diet due to variations in WCS and grain mix NDF. Forage NDF was very similar to the formulated values for diets. This was a critical aspect of the study because a primary objective was to observe the effect of substituting WCS for a portion of fNDF to determine the physical effectiveness of WCS relative to alfalfa silage. Cottonseed hulls were added to the diet to balance NDF and enable the replacement of alfalfa silage NDF with cotton (WCS and cottonseed hulls) NDF on a one-to-one basis.

Rumen pH and VFA Concentration

As the level of WCS substitution increased, the average ruminal pH decreased linearly ($P<0.05$) from 6.28 for cows fed the FCG (21% fNDF) diet to 5.93 for cows fed the HCG (12% fNDF) diet (Table 7). Molar concentrations of acetate and butyrate were unaffected by the level of WCS substitution, but molar concentration of propionate linearly increased with level of WCS ($P< 0.05$). Ruminal fluid from the cows fed the HCG (12% fNDF) diet had 34% higher molar proportions of propionate when compared to the FCG (21% fNDF) diets. Consequently, the acetate:propionate ratio decreased linearly ($P<0.05$) with increased WCS levels. These results correspond with observations made by Mohamed et al. (1988) in which the addition of WCS at 16.5% DM to a basal diet increased the molar proportions of propionate when compared to the control diet. Arieli (1993) also cited several

Table 6. Nutrient composition of diets.

Nutrient	Diet[1]						Feedstuff		
	FCG	LCG	MCG	HCG	LCSF	MCSF	Alfalfa Silage	WCS[2]	Cottonseed Hulls
	(% of DM)								
NDF	30.88	31.30	31.34	31.37	31.11	31.57	40.56	48.71	84.15
fNDF	21.50	18.27	15.41	12.28	18.13	15.41	40.56	0	0
ADF	21.46	21.36	21.65	21.49	21.60	21.79	31.36	35.16	60.22
ADL	4.54	4.47	4.57	4.72	4.62	4.79	7.02	10.10	18.09

[1]Diets are as follows: FCG = Forage control with ground corn (21% fNDF); LCG =Low cottonseed with ground corn (18% fNDF); MCG = Medium cottonseed with ground corn (15% fNDF); HCG = High cottonseed with ground corn (12% fNDF); LCSF = Low cottonseed with steam-flaked corn (18% fNDF); and MCSF = Medium cottonseed with steam-flaked corn (15% fNDF).
[2]WCS = whole cottonseed.
[3] NDF = neutral detergent fiber; fNDF = forage neutral detergent fiber; ADF = acid detergent fiber; and ADL = lignin.

Table 7. Effect of whole linted cottonseed substitution for forage neutral detergent fiber (fNDF) in diets with ground and steam-flaked corn on ruminal pH, VFA concentration, and milk fat percentage.

	Diet[1]						SE[2]		Contrast				
	FCG	LCG	MCG	HCG	LCSF	MCSF	n=5	n=6	L[3]	Q[4]	C[5]	Corn[6]	Inter[7]
pH	6.28	6.13	6.12	5.93	6.07	6.02	0.08	0.07	<0.01	NS[8]	NS	NS	NS
VFA Concentration (mM)													
Acetate	69.3	70.5	70.1	70.4	68.6	66.3	2.84	2.58	NS	NS	NS	NS	NS
Propionate	18.0	20.3	22.6	24.1	23.2	25.4	1.97	1.87	<0.01	NS	NS	0.02	NS
Butyrate	11.4	11.9	11.4	11.7	12.1	12.2	0.77	0.69	NS	NS	NS	NS	NS
Acetate:Propionate	3.98	3.59	3.21	3.02	2.98	2.77	0.22	0.21	<0.01	NS	NS	<0.01	NS
Milk Fat (%)	3.67	3.69	3.57	3.41	3.15	3.19	0.13	0.11	NS	0.05	NS	<0.01	NS

[1]Diets are as follows: FCG = Forage control with ground corn (21% fNDF); LCG =Low cottonseed with ground corn (18% fNDF); MCG = Medium cottonseed with ground corn (15% fNDF); HCG = High cottonseed with ground corn (12% fNDF); LCSF = Low cottonseed with steam-flaked corn (18% fNDF); and MCSF = Medium cottonseed with steam-flaked corn (15% fNDF).
[2]Data for treatment LCG were n = 5; all other data were n = 6.
[3]Linear contrast that compared diets FCG, LCG, MCG, and HCG.
[4]Quadratic contrast that compared diets FCG, LCG, MCG, and HCG.
[5]Cubic contrast that compared diets FCG, LCG, MCG, and HCG.
[6]Main effects of corn source in treatments LCG, MCG, LCSF, and MCSF.
[7]Interaction among corn source and cottonseed level in treatments LCG, MCG, LCSF, and MCSF.
[8]Not significant (*P*>0.20).

studies that indicated that the addition of WCS decreased acetate:propionate ratio. In the current study, these data are probably the result of the composition of the experimental diets used. Diets were balanced to be equivalent in NFC; however, the source of NFC differed for the treatments. As higher levels of WCS were substituted for forage in the diets, the proportion of NFC from corn increased. The NFC provided by corn consists mostly of starch compared to NFC from alfalfa silage, which is primarily pectins. Starches are fermented to propionate or lactate (which is fermented to propionate) more than pectins, and would consequently result in a higher concentration of propionate in the rumen (Firkins, personal communication).

The concentration of propionate was affected ($P < 0.05$) by the corn source in the diet (Table 7). Substituting steam-flaked corn for ground corn increased the concentration of propionate in the rumen and decreased the ruminal acetate:propionate ratio ($P<0.05$). The increased starch availability provided by steam-flaking corn results in a greater proportion of starch digestion in the total tract occurring from fermentation by rumen microorganisms than with ground corn. A higher concentration of ruminal degradable starch has been shown to result in a lower molar proportion of acetate and an increased molar proportion of propionate produced during the fermentation process (Poore et al., 1993). However, no interaction ($P>0.20$) between the corn source and WCS on propionate concentration was detected. The lack of an interaction suggests no decrease in the starch dilution capabilities or effectiveness of WCS when fed in diets with increased starch availability.

Lack of a treatment x time interaction suggests that fermentation curves, as indicated by pH (Figure 1), had similar treatment responses across time. Because chewing activity was not affected by the substitution of WCS or corn source (Table 6), these data imply that WCS

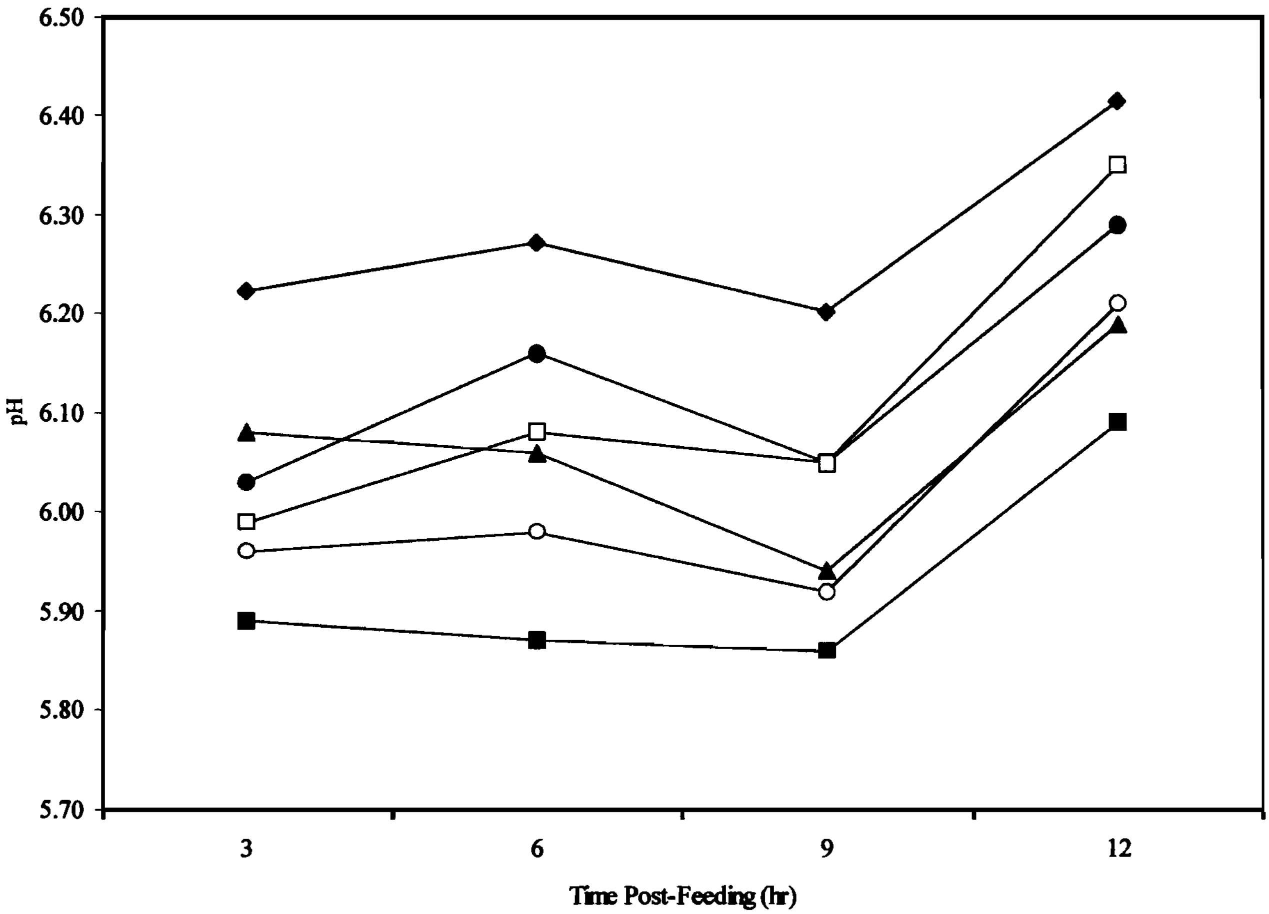

Figure 1. Ruminal pH after feeding for treatments: forage control with ground corn (21% fNDF; ◆); low cottonseed with ground corn (18% fNDF; ●); medium cottonseed with ground corn (15% fNDF; □); high cottonseed with ground corn (12% fNDF; ▲); low cottonseed with steam-flaked corn (18% fNDF; O); and medium cottonseed with steam-flaked corn (15% fNDF; ■).

stimulated enough chewing activity during the 12 hours following feeding to compensate for any increase in VFA production that might have occurred during degradation, especially in diets with high starch availability.

Dry Matter and NDF Intake

The addition of WCS to the basal diet quadratically increased ($P<0.05$) DMI and NDF intake (Table 8). Cows fed the MCG (15% fNDF) diet consumed 14% more DM than cows fed the FCG (21% fNDF) diet. Likewise, NDF intake increased by 17% for cows fed the MCG diet versus the FCG diet. These data support the observations of Mooney and Allen (1997) that the addition of WCS to diets containing both long- and short-cut alfalfa silage increased DMI (24.8 versus 23.0 kg/d) and NDF intake (7.8 versus 7.0 kg/d). Similarly, Clark and Armentano (1993) reported higher DMI for a basal plus WCS diet than for a high fiber alfalfa diet (24.0 versus 22.8 kg/d). The reduction of dietary forage and feed particle size associated with the addition of WCS may have been responsible for the increased DMI due to decreased gut fill or increased rate of passage, which are associated with smaller feed particle sizes of NFFS. Increased NDF intake (Table 8) is due primarily to increased DMI. By design, fNDF intake decreased linearly with increasing WCS substitution ($P<0.05$). Cows fed the MCG (15% fNDF) diet consumed 18% less fNDF than cows fed the FCG (21% fNDF) diet. Conclusions about the effects of the feed particle size on intakes cannot be established in this study because particle size analyses have not been completed at this time.

Substituting steam-flaked corn for ground corn decreased ($P<0.05$) DMI, NDF intake, and fNDF intake (Table 8) even though consumption of rumen degradable organic matter

Table 8. Effect of whole linted cottonseed substitution for forage neutral detergent fiber (fNDF) in diets with ground and steam-flaked corn on total intake and chewing activity.

	Diet[1]						SE[2]		Contrast				
	FCG	LCG	MCG	HCG	LCSF	MCSF	n=5	n=6	L[3]	Q[4]	C[5]	Corn[6]	Inter[7]
Intake													
DMI (kg)	18.5	20.4	21.1	20.8	20.0	19.4	0.49	0.43	<0.01	0.02	NS[8]	0.03	0.16
NDF intake (kg)	5.70	6.36	6.67	6.59	6.19	6.09	0.19	0.16	<0.01	0.04	NS	0.04	NS
fNDF[9] (kg)	3.97	3.68	3.26	2.55	3.62	3.00	0.08	0.07	<0.01	0.01	NS	0.04	NS
Chewing Activity (min/d)													
Eating	271	294	300	284	252	266	28.5	25.0	NS	NS	NS	0.16	NS
Ruminating	514	505	434	520	461	455	44.1	38.7	NS	NS	NS	NS	NS
Total Chewing	785	799	734	805	713	721	52.7	46.2	NS	NS	NS	NS	NS

[1]Diets are as follows: FCG = Forage control with ground corn (21% fNDF); LCG =Low cottonseed with ground corn (18% fNDF); MCG = Medium cottonseed with ground corn (15% fNDF); HCG = High cottonseed with ground corn (12% fNDF); LCSF = Low cottonseed with steam-flaked corn (18% fNDF); and MCSF = Medium cottonseed with steam-flaked corn (15% fNDF).
[2]Data for treatment LCG were n = 5; all other data were n = 6.
[3]Linear contrast that compared diets FCG, LCG, MCG, and HCG.
[4]Quadratic contrast that compared diets FCG, LCG, MCG, and HCG.
[5]Cubic contrast that compared diets FCG, LCG, MCG, and HCG.
[6]Main effects of corn source in treatments LCG, MCG, LCSF, and MCSF.
[7]Interaction among corn source and cottonseed level in treatments LCG, MCG, LCSF, and MCSF.
[8]Not significant (*P*>0.20).
[9]fNDF = forage NDF.

probably remained constant across diets (data not shown). When fed the MCSF (15% fNDF) diet, cows consumed 3% less DM, 9% less NDF, and 8% less fNDF when compared to the MCG (15% fNDF) diet. These results coincide with observations made by Oliveria et al. (1993) that increasing rumen degradable starch via steam-flaking sorghum decreased DMI compared to dry rolled sorghum. In 1997, Allen reported that decreases in ruminal pH may decrease DMI (Allen, 1997). However, the current data indicate that corn source did not directly affect ruminal pH (P>0.20; Table 7). Furthermore, the lack of corn source x WCS interaction for ruminal pH suggests that the starch dilution capabilities of WCS were not compromised in the presence of higher dietary starch availability. These data imply that other factors may be involved with decreasing DM, NDF, and fNDF intakes relative to corn source. In particular, chemostatic regulation of DMI is more important than bulk fill as forage concentration is reduced in high grain diets. The higher starch availability of steam-flaked corn should increase production of VFA, particularly propionate, which has been shown to decrease intake (NRC, 1987). This is supported by data from the current study that show that the concentration of propionate was increased (P<0.05) with the substitution of steam-flaked corn for ground corn.

Milk Fat Percentage

Milk fat percentage was similar between the FCG (21% fNDF) and the LCG (18% fNDF) diet indicating that WCS was as effective as alfalfa silage in maintaining milk fat percentage (Table 7). However, a quadratic relationship (P<0.05) existed between WCS substitution and milk fat percentage. Cows fed the 12% fNDF diet had lower milk fat than cows fed the 18% fNDF diet (3.41 versus 3.69%). These findings differ from results reported by others in which milk fat percentage was not affected or increased with the addition of WCS (Clark and Armentano, 1993; Hawkins et al, 1985; Mooney and Allen, 1997). A weak positive correlation (r^2=0.16) was detected between the acetate:propionate ratio and milk fat percentage across various experiments (Armentano and Pereira, 1997). Therefore, it is possible that this trend towards decreasing milk fat percentage with increasing WCS substitution is related to the negative linear relationship between acetate:propionate ratio and WCS substitution. However, this theory cannot be substantiated. Additionally, a linear decrease in ruminal pH with increasing WCS may promote the trans fatty acid theory of milk fat depression, which would account for the observed quadratic decrease in milk fat percentage. This theory proposes that a decrease in ruminal pH inhibits biohydrogenating bacteria, which are instrumental in the synthesis of saturated milk fatty acids. As a result, the concentration of trans unsaturated fatty acids increases, thereby resulting in milk fat depression (Gaynor et al., 1995).

Substituting steam-flaked corn for ground corn decreased (P<0.05) milk fat percentage (Table 7). Cows receiving the MCSF (15% fNDF) diet had significantly lower milk fat percentage than cows fed the MCG (15% fNDF) diet (3.19 versus 3.57%). This occurrence is due to the increased starch availability of the steam-flaked corn, which was associated with alterations in ruminal fermentation patterns. Increased starch availability is associated with an increased production of propionate during fermentation. The lack of a significant ruminal pH depression supports the glucogenic theory of milk fat depression (Grant et al., 1990). In this theory, higher propionate concentration in the blood increases insulin secretion, which reduces fatty acid metabolization and increases fat uptake by the adipose tissue. As a result, there is a decrease in the availability of milk fat precursors, which may result in a decline in milk fat percentage (Grant et al., 1990).

Chewing Activity

There were no differences among treatments for eating, ruminating, and total chewing activity (minutes/day; Table 8). Similarly, no difference existed among treatments for chewing activity per kg DMI, per kg NDF intake, and per kg of intake from the sum of forage, WCS, and cottonseed hulls NDF (Table 9).

In contrast when NDF from WCS and cottonseed hulls was included, time spent eating per kg of fNDF intake linearly increased ($P<0.05$) with increased level of WCS. However, ruminating and total chewing per kg of fNDF intake increased quadratically ($P<0.05$), especially for the HCG (12% fNDF) diet (Table 9). Total chewing time increased by 58% when cows were fed the HCG (12% fNDF) diet compared to the FCG (21% fNDF) diet. These data support Grant's (1997) observations that low forage diets consisting of high quantities of NFFS tend to increase chewing activity per kg fNDF intake. The quadratic effect indicates that cows may possess an adaptive mechanism that maximizes the efficiency of rumination when NDF is limited. The data from the current study may also indicate that NDF from WCS is as effective at stimulating chewing activity as NDF from alfalfa silage in low forage diets.

The substitution of steam-flaked corn for ground corn had no significant effect on chewing activity (Table 9). However, the lack of a corn source x WCS interaction indicates that NDF from WCS stimulates sufficient chewing activity to produce enough salivary buffers to compensate for the increased VFA production associated with degradation of diets

Table 9. Effects of whole linted cottonseed substitution for forage neutral detergent fiber (fNDF) in diets with ground and steam-flaked corn on chewing activity.

Chewing Activity	Diet[1]						SE[2]		Contrasts				
	FCG	LCG	MCG	HCG	LCSF	MCSF	n=5	n=6	L[3]	Q[4]	C[5]	Corn[6]	Inter[7]
Min/kg DMI													
Eating	14.8	14.7	14.5	13.7	12.9	13.9	1.38	1.21	NS[8]	NS	NS	NS	NS
Ruminating	28.3	25.3	21.4	25.1	23.1	23.7	2.35	2.06	0.17	0.14	NS	NS	NS
Total Chewing	43.1	40.0	35.9	38.8	36.0	37.6	2.71	2.38	0.13	NS	NS	NS	NS
Min/kg NDF intake													
Eating	48.2	46.8	46.0	13.1	41.4	44.3	4.67	4.09	NS	NS	NS	NS	NS
Ruminating	91.9	80.6	67.7	79.7	74.7	75.8	7.98	7.00	0.13	0.13	NS	NS	NS
Total Chewing	140.1	127.5	113.7	122.8	116.2	120.1	9.71	8.52	0.10	NS	NS	NS	NS
Min/kg NDF from forage, WCS, and CSH intake[9]													
Eating	69.0	69.6	68.7	65.7	60.9	65.8	6.61	5.80	NS	NS	NS	NS	NS
Ruminating	131.7	119.6	102.0	121.1	109.5	112.7	11.02	9.67	NS	0.14	NS	NS	NS
Total Chewing	200.7	189.2	170.7	186.8	170.4	178.5	12.76	11.19	NS	NS	NS	NS	NS
Min/kg fNDF intake													
Eating	69.0	81.7	93.9	111.3	70.9	89.8	9.16	8.03	<0.01	NS	NS	NS	NS
Ruminating	131.7	138.5	139.1	204.9	127.4	154.0	14.08	12.35	<0.01	0.03	NS	NS	NS
Total Chewing	200.7	220.2	233.0	316.2	198.3	243.8	16.61	14.57	<0.01	0.05	NS	NS	NS

[1]Diets are as follows: FCG = Forage control with ground corn (21% fNDF); LCG =Low cottonseed with ground corn (18% fNDF); MCG = Medium cottonseed with ground corn (15% fNDF); HCG = High cottonseed with ground corn (12% fNDF); LCSF = Low cottonseed with steam-flaked corn (18% fNDF); and MCSF = Medium cottonseed with steam-flaked corn (15% fNDF).
[2]Data for treatment LCG were n = 5; all other data were n = 6.
[3]Linear contrast that compared diets FCG, LCG, MCG, and HCG.
[4]Quadratic contrast that compared diets FCG, LCG, MCG, and HCG.
[5]Cubic contrast that compared diets FCG, LCG, MCG, and HCG.
[6]Main effects of corn source in treatments LCG, MCG, LCSF, and MCSF.
[7]Interaction among corn source and cottonseed level in treatments LCG, MCG, LCSF, and MCSF.
[8]Not significant ($P>0.20$).
[9]WCS = whole cottonseed; and CSH = cottonseed hulls.

high in starch availability. Consequently, ruminal pH was not affected by the substitution of steam-flaked corn for ground corn in the diet (Table 7).

Physical Effectiveness Coefficient

The calculated physical effectiveness (pe) coefficients for WCS compared to alfalfa silage are shown in Table 10. Whole cottonseed (pe=1.31) was 31% more effective in stimulating chewing than alfalfa hay when fed as part of an 18% fNDF diet. However, whole cottonseed was only 51% as effective as alfalfa silage in stimulating chewing when included in a 15% fNDF diet with high starch availability. These data possibly indicate that diets high in starch availability decrease the physical effectiveness of WCS. However, statistical validation was not possible because only treatment means were used in this calculation. These data were subject to a wide range of variation. Consequently, a more in-depth analysis of the data needs to be completed before these calculated pe coefficients are applicable.

Table 10. Coefficients of physical effectiveness (pe) of whole linted cottonseed neutral detergent fiber (NDF) relative to alfalfa silage NDF based on total chewing time (minutes per day).

	Diets[1]				
	LCG	MCG	HCG	LCSF	MCSF
pe coefficient	1.31	0.63	1.20	<0	0.51

[1]Diets are as follows: LCG =Low cottonseed with ground corn (18% fNDF); MCG = Medium cottonseed with ground corn (15% fNDF); HCG = High cottonseed with ground corn (12% fNDF); LCSF = Low cottonseed with steam-flaked corn (18% fNDF); and MCSF = Medium cottonseed with steam-flaked corn (15% fNDF).

Conclusions

Replacing a portion of fNDF with WCS did not decrease total chewing activity. These results indicate that WCS may be as physically effective as alfalfa silage at stimulating chewing activity. However, substitution with WCS quadratically increased rumination and total chewing time per kg of fNDF intake, suggesting that cows may possess an adaptive mechanism that maximizes the efficiency of rumination when fNDF is limited.

Increasing the dietary concentration of WCS quadratically decreased milk fat percentage in diets with low starch availability. Additionally, substitution with WCS increased the concentration of propionate in the rumen. These results indicate that WCS is as effective as alfalfa silage at maintaining milk fat percentage in diets with at least 18% fNDF.

In the presence of high dietary starch availability, the substitution of WCS for fNDF resulted in decreased milk fat percentage and decreased DMI, NDF intake, and fNDF intake. Furthermore, replacing fNDF with WCS in diets with high starch availability increased the concentration of propionate in the rumen. However, a lack of corn source x WCS interactions suggests that other factors, such as the dietary source of NFC, may alter the apparent effectiveness of WCS. Further research is necessary to investigate possible interactions between WCS and dietary components.

Definition of Terms

Dry matter (DM) - the proportion of feed remaining after water is removed; usually expressed as a percentage.

Fiber effectiveness – the ability of a fiber source to stimulate chewing activity and maintain milk fat percentage.

Lyophilize – process of freeze-drying

Neutral detergent fiber (NDF) – the most common analysis of fiber; the fraction of fiber composed of cellulose, hemicellulose, and lignin components of plant tissue.

Non-fiber carbohydrate (NFC) – source of carbohydrate other than the cellulose, hemicellulose, and lignin components of plant tissue.

Volatile fatty acid (VFA) – acids produced during the fermentation process by ruminal bacteria; composed primarily of acetate, propionate, and butyrate.

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